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Astrophysics in 1991[1]

VIRGINIA TRIMBLE

Astronomy Department, University of Maryland, College Park, Maryland 20742 and Physics Department, University of California, Irvine, California 92717-4575

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ABSTRACT. Science, notoriously, progresses amoeba-like, thrusting out pseudopods in unpredictable directions and dragging the rest of the body after or, occasionally, retreating in disorder. This review attempts to shine a narrow and not unprejudiced beam of light on areas of astrophysics where the author believes that something interesting happened in 1991. Length scales range from the kilometers of comets to the gigaparsecs of cosmology, and time scales from milliseconds upward. Eight self-contained sections discuss the surface of Venus, late activity in Comet Halley, convective overshoot, blue stragglers, new examples and kinds of X-ray binaries and recycled pulsars, hard X and γ rays from the galactic-center region, microlensing, and biased cold dark matter. The last two sections contain very short descriptions, with references, of a number of items that did not fit into the main sections but seemed a shame to leave out.

1. INTRODUCTION

The idea for this article, putatively the first of a series, originated with the Editor, but struck an immediate responsive chord in the author, who was soon wandering the corridors humming phrases like "Halley's last gasp," "Lying cold and dead," and "everything you ever wanted to know about convection but were afraid to ask Schwarzchild about." The goal is to focus on some issues that look closer to resolution as a result of events, observations, ideas, and calculations concentrated in the last year. Given the lead time for publication, 1991 necessarily means roughly the academic year 1990 October–1991 September.

"Astrophysics" has been interpreted broadly to include all parts of astronomy that do not actually require you to recognize the constellations or predict the phases of the moon. Many things had to be left out—and my deep apologies to anyone generous enough to be reading this after not finding his name in the list of references. Several very important issues have been intensively discussed elsewhere, for instance, star formation in the "Bahcall report" (National Academy of Sciences 1991). And galaxy formation is arguably the single most serious problem in astrophysics today; but, as Ehrenfest is supposed to have said, "It is difficult to explain something even when you understand it, and almost impossible when you don't."

An effort has been made to provide references to reasonably accessible books and journals. My failures will be recognizable by citations essentially of the form Rumor (1991).

2. MAGELLAN AT VENUS: NO SUBDUCTION HERE

The Earth is (mercifully) very different from the other terrestrial planets. Some of the differences we think we understand. The unique oxygen-bearing atmosphere is a product of plant life. The terrestrial dipole magnetic field arises from currents in a rotating fluid core not duplicated elsewhere, because Venus rotates too slowly, and Mars is too small to have developed and maintained a molten, metallic interior zone. The processes of plate tectonics and continental drift (Sullivan 1991) responsible for the Earth's surface features are apparently also, and more surprisingly, unique.

The Earth's surface is marked by high, granitic continents, contrasting with lower, basaltic ocean basins, many cut by spreading rift valleys. The whole is divided into a dozen or so major lithospheric plates, each containing some land and some ocean, that are carried over the surface by convection in the underlying mantle. Earthquakes and other violence trace out the boundaries. Where plates diverge at rift valleys, new basaltic crust forms from partially melted mantle material (as in the mid-Atlantic ridge). Convergence results in continental rock piling up into mountains (the Andes, Alps, and Himalayas), while oceanic crust can be dragged back down into the mantle in trenches or subduction zones like Mindanao. Reprocessing of subducted basalt into the less dense rocks of island arcs has gradually produced continental crust. Transverse motion leads to active fault zones including the infamous San Andreas; and nothing stays put for more than about 10^8 yr.

The moon, Mercury, and Mars are doing nothing of the sort, as the first close-up photos quickly showed (Lang and Whitney 1991). Two and a half of them retain ancient surfaces, pockmarked by impact craters, mostly three or more billion years old (though only the moon rocks have absolute ages measured from radioactivity in Apollo samples). The other (northern) half of Mars consists of low-lying volcanic plains, traversed by a few enormous cracks and pierced by volcanos larger than any on Earth. Counts of impact craters at various heights on the volcanic slopes reveal recent lava flows near the peaks and very ancient ones further down. Martian volcanos, in contrast to terrestrial ones, have their roots dug in permanently. In addition, there are no large scale features remotely resembling the East Pacific Rise, the East African rift valley, or the subduction trench off the coast of Chile. The moon, Mercury, and Mars have no plate tectonics, presumably because, being small, they have cooled off too much for mantle convection to take place.

Venus was long a mystery. Nearly as massive as the Earth, it ought to have a similar internal structure, leading to similar plate tectonic features. But the cloudy veil over its surface was only gradually pierced by radar mapping from Earth-based telescopes, Venera 15 and 16, and Pio-

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neer Venus. Revealed was a surface much flatter than the Earth's (Lang and Whitney 1991), with less obvious continent/basin distinctions and no large scale features resembling subduction zones, rift valleys, or island arcs (like the Caribbean islands).

Magellan (formerly the Venus Orbital Imaging Radar) arrived in August 1990 and began sending back radar maps and altimeter data about September 15th. Most of the surface has now been scanned at least once, and mapping is expected to continue through several more rotation periods. Preliminary results were presented at the Seattle meeting of the American Astronomical Society and published in the course of the spring (Campbell et al. 1991; Phillips et al. 1991; Saunders 1991; Saunders and Pettengill 1991).

In summary, the surface of Venus is an active one, though somewhat less so than the Earth's, but the dominant processes are different in partially comprehensible ways. Impact craters are recognizable, though the dense atmosphere keeps their ejecta from spewing as far as on the moon (etc.), and the warm (730 K) surface allows melted rock to remain fluid longer and flow further. Numbers of such craters are surface age indicators as on other solid planets and moons (except the Earth where they are quickly eroded).

About half the surface is younger than 10^9 yr, and the replacement rate requires lava production of about 1 km^3 yr^{-1}, roughly 10% of the terrestrial rate, though no volcanos have been caught in eruption so far. Fresh lava does not appear at elongated spreading centers like our mid-ocean ridges. The most promising candidate for such a rift, Ogda Regia, has none of the parallel ridges or transform fault offsets expected of such a structure. Instead, lava predominantly appears in isolated volcanoes with stable locations (Martian style), presumably located over mantle plumes. On Earth, lithospheric plates move gradually over such plumes, so they show up as island chains (Hawaii is the best known example) rather than as single large structures.

Rising and/or sinking plumes and blobs apparently also lift, move, and pile up the highland (continent-like) areas, of which the largest are Ishtar and Aphrodite. Because the rocks are warmer, bending and stretching of the surface is more common, relative to breaking and fracturing, than on Earth, though sharp-edged fracture features (e.g., grabens) also occur. Some strain patterns are coherent over hundreds of kilometers and must reflect underlying mantle dynamics. The fault zones are, however, 100–300 km wide, like those of terrestrial continents rather than ocean basins, even in the lower-lying regions. And there are no subduction zones where crust can be returned to the mantle for additional processing.

Cytherean highlands rock must, therefore, have been produced by gradual vertical differentiation rather than by recycling. Such recycling is probably essential to ore production on Earth; so in addition to the other disadvantages of life on Venus, copper wires and gold coins to pay for them would be in short supply.

The slowness of Cytherean rotation probably makes mantle convection and so the overlying crustal dynamics different from ours. But, in addition, subduction on Earth requires basalt to increase its density by cooling (all major zones are under water). The surface of Venus may just be too hot for basalt ever to subduct. If it is this simple, then the sobering thought arises that a runaway greenhouse process on Earth could someday destroy not only our biosphere, atmosphere, and hydrosphere, but even the processes that maintain our mountains and valleys.

3. HALLEY'S LAST GASP

Many astronomers are, quite properly, fond of comets for their own sake (Heubner 1990). For others, the chief charm lies in the cometary potential for preserving pristine samples of the material from which the solar system formed, more or less free of the effects of chemical and physical processing. Unexpected activity on the part of Comet P/Halley suggests that significant processing can occur more than 10 AU from the Sun, meaning that, in order to collect an undisturbed sample, we may need to excavate a comet that has never come even that close.

The previous record for far-out detectability belonged to Comet Bowell (1982 I), followed to 13.6 AU by Meech and Jewitt (1987). At that point, it still displayed some coma activity. With a nominal orbital semimajor axis of 3×10^4 AU, Bowell (like the preceeding record holder, traced to 10 AU in 1922) had presumably approached the Sun at most a very few times before. Meech and Jewitt (1987) attributed its unusually prolonged activity to its near-virgin state.

Halley's late flare casts doubts on that interpretation. In 1990 February, P/Halley had faded to $V=23.9$–24.9 and had no resolvable coma (though some was arguably contributing to the mean brightness). In 1991 February, when the comet was 14.3 AU from the Sun, observers at ESO (West et al. 1991) found, much to their surprise, that it had brightened to $V_{tot}=18.9$, and much of the light was coming from an elliptical coma of $3.74\times2.69\times10^5$ km extent. A ridge of high surface brightness moved outward between February and March, at a rate suggesting ejection in 1990 December. The color and spectrum indicate that the ejecta were primarily dust, not gas. Because the central surface brightness had faded, the discoverers thought it likely that the event was about over in April, when Halley had reached heliocentric distance 14.6 AU. Up to then, about 10^8 kg (10^{-6} of the nuclear mass) of dust had found its way into the coma.

West et al. (1991) defer to a later paper a discussion of the possible causes of the event. Hughes (1991) explored several alternatives, including some sort of internal energy release and dust escaping through a fissure to be electrically elevated by the solar wind. He concluded that a collision with an outlying asteroid was the most probable of the mechanisms and suggested that 10^{-4} or more of Halley's nuclear mass might have been lost in the impact. Further data and thoughts on the probable cause will, of course, be of great interest. But the mere fact of the event suggests that comets are subject to physical and chemical processing, at least in their outer layers, even very far from the Sun.

4. THE TRUTH ABOUT CONVECTIVE OVERSHOOT

Convective overshoot is important for starts of 1.5–2.5 $M_\odot$ and otherwise not (Giménez 1991; Andersen 1992; Stothers 1991). Now that the answer is clear, what was the question, and what difference does it make? (And should we believe it?)

Notoriously, there is no real theory of how turbulence and convection behave in astrophysical objects. Nearly all

calculations of stellar structure and evolution that include enough other correct physics to permit comparison with observations treat convection in the mixing length approximation. That is, you check whether the temperature gradient is steeper than the adiabatic one (so that a displaced fluid element would keep going). If it is, then energy transport is attributed to hot and cool blobs that rise and fall, at speeds determined by gravity acting on their difference in density from the surrounding average, through a characteristic distance, the mixing length (typically one or two pressure scale heights). Then they exchange energy with their surroundings and come into thermal equilibrium. Convective zones are, as a rule, well mixed.

If the temperature gradient is shallower than the adiabatic one, radiation is assumed to carry all the energy outward. Radiative zones can have composition gradients in them. On the main sequence, stars up to about 1.2 $M_\odot$ have radiative cores and convective envelopes, more massive stars the opposite. Several very interesting improvements on this scheme are under investigation (Canuto and Mazzitelli 1991; Cattaneo et al. 1991), but are not yet ready for direct confrontation with observed properties of stars.

Meanwhile, the mixing length approximation has built into it two logical swamps, presently crossed by bridges called convective overshoot and semiconvection. First, at the edge of a convective zone, where the temperature gradient drops to the adiabatic value, the force or acceleration on a blob drops to zero, but its velocity probably won't. Convective overshoot mixes half a scale length or so beyond the nominal edge of a convective core or envelope to allow for the blobs to decelerate to zero velocity. An overshooting core therefore has access to more hydrogen fuel and can burn longer and leave a larger central helium zone than does a non-overshooting one. An overshooting envelope in a star like the Sun can take fragile nuclides like deuterium and lithium down deep enough for them to burn, where a non-overshooting one would not (Skaley and Stix 1991).

The second inconsistency occurs when an elderly convection zone (normally in the core) has developed a sharp composition discontinuity at its edge. The adiabatic temperature gradient

$$\nabla_{ad}=\left(1-\frac{1}{\gamma}\right)\frac{T}{P}\frac{dP}{dr}$$

is continuous across the edge, as long as the gas is fully ionized, but the radiative gradient

$$\nabla_{rad}=\frac{3P\kappa L(r)}{16\pi acGT^4M(r)}$$

is discontinuous, and larger outside, because the opacity κ has an electron scattering piece that is larger where the hydrogen abundance is larger. Thus, just outside the core, the radiative temperature gradient is actually larger than the adiabatic one, though we have declared this to be a radiative zone. Letting the convective core take in a bit more mass simply shoves the problem outward slightly. Semiconvection is the smoothing of the composition gradient, by non-convective processes, to remove this contradiction. In practice, especially for the larger convective cores characteristic of massive stars, the two processes can be almost indistinguishable (Caloi and Mazzitelli 1991).

In addition to the effects on stellar lifetimes and surface compositions, overshoot and semiconvection will affect the main sequence mass that is the dividing line between white dwarf and neutron star progenitors and (via the effect of the shape of the hydrogen profile left behind) will determine the extent of excursions to red and blue during advanced stages of evolution. As a result, a significant subset of the astronomical community has a vested interest in the answer to the question: Do real stars experience significant convective overshoot?

Now that we have finally arrived at the question, the answer requires a bit more exploration as well. First, if you really want to extract an answer by comparing observed stars with models, then good data, models that incorporate the best possible versions of other parts of stellar physics, and a clear understanding of the evolutionary state of the stars are essential. For instance, looking at blue stragglers (Sec. 5) in comparison with models that use Cox and Stewart opacities (Sec. 10.2) may not be a good choice (Brocato and Castellani 1991, commenting on work by Napiwotzky et al. 1991).

Second, the range of stellar evolution models and isochrones with which comparison can be made handle the processes rather differently. Hejlesen (1980) stopped his convection sharply where forces on the blobs go to zero, but did quite a lot of semiconvective smoothing. He used Cox and Stewart opacities. VandenBerg (1985) similarly had no overshoot, but incorporated larger, more recent opacities from the Los Alamos Opacity Library, as do all the other model sets mentioned here. Maeder and Meynet (1988, 1991) extended their convection zones 0.25 pressure scale height beyond the $\nabla_{rad}=\nabla_{ad}$ layer for main sequence stars $\geqslant 1.3\ M_\odot$, 0.125 scale height at 1.15 $M_\odot$, and not at all (because there is no convective core) for lower masses. Claret and Giménez (1991) adopted a similar prescription. Bertelli et al. (1986) included a whole pressure scale height of overshoot. Castellani et al. (1990) put the edges of their convective cores where velocity, rather than acceleration, went to zero, thus permitting both processes to operate, but not telling us explicitly how much overshoot occurs.

Third, we do not know M, L, R, age, and composition accurately enough for any one star, except perhaps the Sun, to permit meaningful absolute comparisons. Thus the relevant investigations deal either with well-studied spectroscopic, eclipsing binaries or with HR diagrams of whole clusters. This permits one to calibrate out some of the variables by requiring the stars to have the same age and initial composition.

Recent work of this type that deduces a need for convective overshoot (of 1/4–1/2 scale height) in main sequence stars of 1.5–2.5 $M_\odot$ includes studies of Capella (Batten et al. 1991), BW Aqr (Clausen 1991), NGC 3680 (Anthony-Twarog et al. 1991), and NGC 2243 (Bergbusch et al. 1991). On the other hand, Aparicio et al. (1990, 1991) find better fits to the HR diagrams of the old open clusters King 2 and King 11 with overshoot suppressed so that composition gradients are not eroded, at least for stars up to 1.6 $M_\odot$. Castellani et al. (1990, 1991) seemingly occupy a middle ground, by allowing for arbitrary amounts of overshoot in their models, but concluding that it is not the explanation for many of the phenomena for which it has been invoked. The reader is invited to conclude for himself that more work is needed.

If the answer given in the first paragraph is right, then we need to ask why. My impression is that lower mass stars have such small convective cores and higher mass stars such large cores that half a scale height here or there is a small perturbation on the total burning process. In addition, we will have to revise some of the numbers we carry around with us. The Hyades is normally thought of as a relatively young open cluster, but it ages to 1.2 Gyr with appropriate amounts of convective overshoot (Anthony-Twarog et al. 1991).

5. BLUE STRAGGLERS

Blue stragglers, like the solar-neutrino problem, challenge our claim to have understood basic main sequence stellar structure and evolution. Several 1991 observations seem to have made the challenge a considerably more difficult one to meet, though a couple of new theoretical ideas are in there fighting. Broadly defined as stars that occupy positions in the HR diagram that should only be occupied in a younger stellar population than the one you happen to be looking at, blue stragglers can be found in globular clusters (Sarajedini and Da Costa 1991), open clusters and associations (Strobel 1991), and among the field halo stars of the Milky Way (Stetson 1991) and its attendant dwarf spheroidal galaxies (Mateo et al. 1991), where the brightest ones belong to the SX Phe subclass of anomalous Cepheids. A narrower definition restricts the name to stars that seem to be straggling into the part of the main sequence bluer and brighter than the turnoff defined by most members of a given cluster. There is no reason to believe (and several to disbelieve) that the physical cause is the same for all the objects in the class.

Blue stragglers are featured in this review primarily because of a recent analysis (Milone et al. 1991) of the three eclipsing ones in the globular cluster NGC 5466. Careful deconvolution of the light curves of these two contact and one Algol-like system reveals that, in each case, the secondary is at the top of the cluster main sequence and the primary itself still straggles. In other words, the fact of their being binaries has not actually solved the problem. Another reason for focusing on blue stragglers this year is that 47 Tuc, once advertised (Hesser 1988) as a cluster without any, reveals about 20 in its first *HST* image (Paresce et al. 1991). All are deep in the cluster core, where ground based observations could not probe. The existence of this population undoubtedly has significance for the dynamical and chemical evolution of the cluster that needs to be thought about.

Nemec (1989) has reviewed ways of making blue stragglers and related stars, and new ideas continue to appear. The inventory, with predictions for properties of the objects formed, includes: (a) late star formation (mass could be anything; surface composition unlikely to show effects of nuclear processing; not possible for globular clusters), (b) mass transfer and/or coalescence in a close binary (mass not more than twice turn-off mass; surface likely to be depleted of lithium and other processing possible; stars should rotate rapidly), (c) near-complete mixing at helium flash (mass about equal to turn-off; surface likely to be processed), (d) gradual mixing throughout main sequence life by enhanced meridional circulation or unknown processes (mass up to 3–4 times turn-off; surface could be unprocessed), (e) mass transfer, star exchanges, and mergers when two binaries interact in a dense cluster core (mass up to three times turn-off; surface probably processed; stars rotate rapidly; Leonard and Fahlman 1991; Goodman and Hernquist 1991), (f) less than the usual amount of mass loss (assumed to be large) during early main sequence evolution (mass limited to 1.5–2 times turn-off; surface should be particularly unprocessed), and (g) intervention by astroengineers anxious to prolong the life of their host star (Beech 1990). You might think it would be easier to move (but my grandmother clung to the house she and Grandpa Farmer had built in 1907, though the neighborhood changed beyond recognition). Luckily the first publication of this idea occurred slightly outside our time window, justifying benign neglect.

The proper test of these mechanisms is comparison with observations. Mathys (1991) has summarized the situation well by saying that no one can account for everything we see, even among the blue stragglers of a single cluster (M67 in his case).

Consider the globular clusters first. The combined straggler population of five clusters (Sarajedini and Da Costa 1991) has a luminosity distribution that drops sharply at $M_V = +2.6$, corresponding to a zero-age star with twice the turn-off mass, but goes to zero only at $M_V = +1.9$, the maximum brightness achieved by the same star near hydrogen core exhaustion. A clear signature of binary mergers, you say (and so say the authors). But this cannot quite work for the eclipsing binary subset of NGC 5466 objects, whose primaries alone are both bluer and brighter than the turn-off. Models based on encounters of two close binaries sound like a perfect solution, but the contact binaries made this way all merge so quickly that we should not see any of them, let alone two in one cluster (Goodman and Hernquist 1991). Concentration of the stragglers into the cluster cores, indicating higher than average masses, is common but not universal (Sarajedini and Da Costa 1991). Finally, there is no very obvious correlation between existence or numbers of blue stragglers in a globular cluster and its other properties (which might guide us to the right formation scenario), once allowance is made for a plethora of observational selection effects.

Among open clusters, blue stragglers seem to be more common in those with solar metallicity than in metal-poor clusters (Strobel 1991). Only M67 is relaxed enough for mass segregation to be expected, and indeed its stragglers are centrally concentrated. But they present other problems, described by Mathys (1991), Hobbs and Mathieu (1991), and Pritchet and Glaspey (1991). The stars are lithium poor (which ought at least to rule out the explanation in terms of anomalously low main sequence mass loss; King 1991). But, in addition, some show enhanced abundances of *s*-process elements and distorted CNO ratios. Most (not all) are slow rotators for their spectral types, and some (not all) show no evidence for radial velocity variations. Mathys (1991) suggests an affinity with the Am stars, which are not very well understood either. I wonder about some relationship with the stars of spectral type S, which come in two classes, with and without technetium (half life $\sim 10^6$ yr). The latter, according to Johnson (1991) are invariably binaries with (probably) white-dwarf companions, and the abundance anomalies were produced in the now-vanished more massive primaries and dumped onto the stars we see.

All in all, blue stragglers seem to be both inadequately understood and insufficiently appreciated. So indeed said

the Editor twenty years ago (Bond and MacConnell 1971; Bond and Perry 1971).

6. RECYCLED PULSARS AND X-RAY BINARIES: REMARKABLE PROLIFERATIONS

Rapid increases in the number of known recycled pulsars (rapidly rotating, but magnetic fields $\lesssim 10^{10}$ G; about half binaries) and in the physically distinct categories of X-ray binaries (with neutron star or black hole accretors) have occurred in the last year or so. Because at least some of the pulsars are thought to have been spun up by accretion in X-ray binaries (XRBs), each of the two increases affects how we think about the other. Trimble (1991) is one possible source for background material on both sorts of objects.

6.1 Pulsars

For several years after their discovery, "the" binary pulsar (1913+16, Hulse and Taylor 1975) and "the" millisecond pulsar (1937+11; Backer et al. 1982) remained unique. The single object was quickly interpreted as one spun up by binary accretion and then liberated (Alpar et al. 1982), thus linking the two as descendants of X-ray binaries. Improved techniques for acquiring and processing data for pulsars with low flux levels and short, sometimes varying, periods have rather suddenly expanded the inventory of binary and millisecond pulsars to about three dozen. Like the XRBs, they are strongly overrepresented in globular clusters.

Most remarkably, 47 Tuc now has 11 pulsars observed (0021−72C to 0021−72M, Manchester et al. 1991), including six binaries, four definitely single, and one uncertain. All have periods between 1.7 and 6 ms. This is, frankly, an embarrassment of riches. Because the cluster is distant, the pulsars seen must represent only the tip of the luminosity function, if it is anything like that for field recycled pulsars. The implied total population in globular clusters is, therefore, in the range 10^{3-4}. Thus arises a statistical problem. The clusters harbor ten bright, low-mass x-ray binaries (including two recently spotted by *ROSAT*, Predehl et al. 1991), and the pulsars cannot be more than 10^{10} yr old. Thus either a typical cluster XRB lasts only 10^7 yr, or we are doing the wrong calculation. In the former case, one mostly just shifts the problem to that of making enough XRBs.

The statistical problem was recognized for other clusters even before the crowd in 47 Tuc was announced. It has prompted a revival of theoretical work on alternative ways of making low-field, rapidly rotating pulsars in cluster environments, as well as a NATO workshop on the subject (van den Heuvel and Rappaport 1991). One possibility, long recognized, is accretion-induced collapse (Bailyn and Grindlay 1990), in which binary accretion onto a white dwarf drives it over the Chandrasekhar limit and so into core collapse. It is possible to avoid a prolonged XRB phase, so that the system first appears as a rapidly rotating pulsar.

More interesting are encounter processes specific to the cores of dense clusters, especially ones that have undergone core collapse (as a majority of the pulsar hosts seem to have). The processes include tidal capture (Johnston and Kulkarni 1991), collisions (Rasio and Shapiro 1991), and star exchange between an ordinary binary in the cluster and a neutron star left from when the cluster was young (Phinney and Kulkarni 1991). Collisions can leave a disk around a neutron star, so that it spins up without passing through an X-ray phase. And a combination of the processes may well produce as population of cluster pulsars much like the one seen (Phinney in van den Heuvel and Rappaport 1991).

The 47 Tuc inventory includes the third example of a binary pulsar whose radiation is apparently ablating a very low mass companion, and so driving off a stream of gas that eclipses the pulsar during a large part of the orbit period. The first of these, 1957+20 (Fruchter et al. 1988) counted as a discovery; the second, 1744+24A, in Terzan 5 (Nice et al. 1990, just within our time window) was a confirmation; and 0021−72J (Manchester et al. 1991) now renders them "a well-known class of astrophysical object." This is not quite the same as being sure that the relevant physical processes have been completely understood (Emmering and London 1991), but it is reasonable to conclude that an additional end point for binary neutron stars (besides merger, disruption, and eternal orbiting) has been identified.

6.2 X-Ray Binaries

Meanwhile, over in the X-ray regime, two of the three satellites that were still gathering data as this is being written have found examples of what are arguably new classes of X-ray binaries. The *ROSAT* ones are so soft (kT=20–40 keV) that similar sources in the plane of the Milky Way will be absorbed into invisibility. The new examples are RX J0527.8−6954 and Cal 83 (Greiner et al. 1991) in the LMC and a couple of SMC sources. Cal 87, previously known in the LMC, also belongs to the class. The discoverers have suggested that these very soft XRBs may be the progenitors of a significant subset of recycled pulsars. Their nondetectability in the galactic disk has then distorted our impression of the lifetimes needed to provide an evolutionary connection. Spotting some of them in high-latitude globular clusters would greatly strengthen the connection, and pointed *ROSAT* observations have been scheduled for the purpose.

GINGA, on the other hand, has found seven new transient x-ray binaries, four with hard, power-law tails to their spectra of the sort displayed by the established black-hole candidates Cyg X-1 and A0620−00 (Inoue 1991). The total number of black hole systems implied is sizable. The GINGA discovery rate has been one or two per year, all within about 3 kpc (assuming luminosities not in excess of the Eddington limit). Two have recurred (A0620−00 was an optical nova in 1917, and GX 2023+33 was V404 Cyg or Nova Cygni 1938), suggesting a typical period near 50 yr. Thus the total number of transient black-hole candidates in the galaxy is apparently at least $(1\text{–}2)\times 50\times(10/3)^2$ or 500 to 1000 (Inoue 1991; Tanaka 1991), making them more numerous than the 100 or so recognized galactic X-ray binaries with neutron-star accretors. This is not a very comfortable result, though if the rest of the GINGA transients are neutron star systems with similar luminosities and recurrence times, then the real number of neutron star XRBs is at least in the same ball park as the black hole one.

Two hard sources near the galactic center, studied by Granat, GRS 1758−258 and 1E 1740.7−2942 (about which more in Sec. 7), have also been proposed as having

black hole rather than neutron star components (Sunyaev et al. 1991a). Clearly the issue can only be completely settled when spectroscopy permits dynamical determinations of the masses of the accreting stars.

ROSAT has also found what seems to be the first X-ray binary in an open cluster, RX J0146.9+6121, on the outskirts of NGC 663 (Motch et al. 1991). The optical identification is one of the Be stars in which the cluster is known to be remarkably rich. Given all these tentative sorts of new objects, it is reassuring to learn that, as surveys extend to fainter flux levels, most of the galactic x-ray sources found continue to be examples of known classes (Yamauchi and Koyama 1990).

Anyone who was expecting this section to end with a discussion of the pulsar with a planetary-mass companion (1829−10; Bailes et al. 1991) is going to be disappointed. Instead, I would like to call attention to what may be a new class of cataclysmic variable, the SW Sex stars, in which the radial velocity curve lags the expected phase (relative to the light curve) by as much as 0.2 of a period (Thorstensen et al. 1991).

7. THE GREAT ANNIHILATOR: $e^{\pm}$ GAMMA RAYS FROM THE GALACTIC-CENTER REGION

The central portions of our galaxy look remarkably different in each of the wavelength bands that reach us from there and host a dozen or so complex and sometimes mysterious structures and phenomena (Morris 1989). Not least of these is emission in the electron–positron annihilation line at 511 keV. But marginal detectability and poor resolution in energy and angle have made it remarkably difficult to establish the basic properties of the source. Is it compact or extended; hot, cold, or gravitationally redshifted; steady, variable, or occasionally even nonexistent; and, therefore, what is its real relationship to the galactic center, and does it provide evidence for a sizable black hole there (Lingenfelter and Ramaty 1989)?

Three new data sets appear to have resolved most of these. The data come from (a) the balloon-borne FIGARO (French–Italian GAmma Ray Observatory) II telescope (Niel et al. 1990), (b) the Goddard balloon-born GRIS (Gamma Ray Imaging Spectrometer; Gehrels et al. 1991), and (c) the French Sigma telescope on the Soviet *Granat* space-based observatory (Sunyaev et al. 1991a,b). *GRO* (the *Gamma Ray Observatory Satellite*) is just beginning to contribute and should eventually provide better energy resolution and temporal coverage than have so far been available (Kurfess et al. 1991).

The provisional answers to all the questions, except the last, appear to be "yes." That is, there is a steady component distributed for many degrees along the galactic plane; but there is also a variable, compact component, coming from quite close to the galactic center, which is the brighter of the two when it is in its high state. The diffuse component has a line width consistent with zero temperature (and no Doppler or gravitational line shifting); while the compact one has a width of about 3 keV, corresponding to a temperature near 10^5 K or a Doppler width of 2000 km s^{-1} (but no obvious redshift). Both have an associated softward continuum, presumably due to three-photon annihilation of positronium. And—this is the stinger—the compact component is not coincident with either Sgr A* or IRS 16, the radio and infrared objects that are the main candidates for the dynamical center of the galaxy.

The hard X-ray flux from the galactic-center region has contributions from at least six sources, none actually at the center. The most variable, and frequently the brightest, is the X-ray binary 1E 1740−2942, whose resemblance to Cyg X-1 suggests the accretor could be a black hole. There is also a radio source within 1″ of its position (Leahy 1991). And, according to the GRIS and Sigma/Granat data (Sunyaev 1991), this X-ray binary is the source of the variable $e^{\pm}$ radiation. A black hole perhaps, but surely not one of the 10^{5-6} $M_{\odot}$ as has been advocated for the true center!

8. THE YEAR OF THE MICROLENS

The focusing of light by a gravitational field has a long history, apparently predating general relativity (Lenard 1921 on 1801 work by J. Soldner). All early post-GR discussions envisioned stars as both object and lens (Eddington 1923; Frost 1923 as quoted by Zwicky 1937; Chwolson 1924; Einstein 1936). Fritz Zwicky (1937) was the first to point out that the lensing of one galaxy by another was a good deal more likely. Indeed all confirmed cases are of that sort, provided you are willing to count quasars and clusters as honorary galaxies.

No sooner, however, was the ink dry on the issue of *Nature* announcing the discovery of the first lensed quasar, 0957+561 (Walsh et al. 1979) than Chang and Refsdal (1979) proposed that stars within the lens could produce substructure in the images in both space and time. Though the angular variations are far too small to resolve, one might reasonably expect to learn something about interior details of both the lensed and lensing object from the temporal variability. We seem finally to be on the threshold of this happening. There are some observations in hand and several dedicated observing programs in various states of readiness. And the phenomenon has acquired the name microlensing to distinguish it from the kind due to whole galaxies.

In the case of quasars lensed by foreground galaxies, the trick is to separate variability caused by stars in the lens moving across the line of sight from intrinsic variability of the quasar itself. The microlensed component is, in principle, identified by being perfectly gray—all wavelengths respond simultaneously to changes in lens geometry (provided the lens is in a vacuum). Intrinsic changes in luminosity are unlikely to do this. Nevertheless, there is still active debate on the extent to which microlensing contributes to the variability of BL Lac objects (Hewett 1991) and of 0957+561 (Falco et al. 1991; Schild 1990). The most persuasive candidate for microlensing so far is perhaps a $\approx 100^{d}$ event in the optical light curve of 2237+030 (Nadeau et al. 1991; Wambsganss and Paczyński 1991).

Meanwhile, technology for recording and processing large numbers of images has advanced to the point where it is possible to look for the lensing of background stars by stars and other compact objects in our own galaxy. Several different cases are under consideration. First, one can possibly discover extra-solar-system planets and binary stars this way (Mao and Paczyński 1991). Second, and perhaps of wider interest, lensing can reveal brown dwarfs, cold white dwarfs, black holes, and other potential dark matter candidates in the halo of the Milky Way if they have masses between about 10^{-6} and 100 $M_{\odot}$, corresponding to events that would last hours to years and amplify the

lensed star by a few tenths of a magnitude (Nemiroff 1991; Griest et al. 1991; Krauss and Small 1991).

The Large Magellanic Cloud provides the richest field of objects to be lensed by things in our own galaxy, and about one star in 10^6 there should be experiencing a detectable lens event at any given instant (Griest 1991). Looking in the direction of Baade's window can test the methodology, because known disk stars must produce some lensing of the bulge stars (Paczyński 1991). LMC and galactic center targets both mandate work from the southern hemisphere.

A French project (Ferlet 1991) has already collected and processed 28 ESO Schmidt plates (not yet enough to expect to see one event) and, in Fall 1991, will begin collecting a couple of hundred plates and CCD images, expected to contain about 10 events. They will look at Baade's window when the LMC is not available. A second collaborative project, involving Mt. Stromlo Observatory, Lawrence Livermore National Laboratory, and UC Berkeley (Griest et al. 1991; Freeman 1991) has just finished assembling its telescope and hopes also to be collecting CCD images within a few months. In these days of political correctness, one has to admire their decision to say they are looking for MAssive Compact Halo ObjectS or MACHOS!

9. BIASED COLD DARK MATTER: NOT DEAD, ONLY RESTING

The biased cold dark matter scenario attempts to provide simultaneous answers to two outstanding questions about the universe—what is most of it made of, and how did galaxies form? See Trimble (1987) for some of the background to these problems. The idea, in outline, is (a) that 80%–95% of the mass of a critical-density universe consists of non-radiating, weakly interacting particles ("dark") of rest mass $\gtrsim 1$ keV or with properties otherwise such as to make them non-relativistic when the temperature of the universe dropped below the 3000 K needed to ionize hydrogen ("cold"), (b) that initial perturbations in the density of the cold dark matter (CDM) arise from quantum mechanical statistical fluctuations followed by an epoch of inflation, and so consist of random Gaussian wiggles with equal power on all length scales (the Harrison–Zeldovich spectrum), and (c) that galaxies form only at the highest density peaks, so that they are more strongly clumped than the underlying matter density by a constant factor $b=(\delta N/N)/(\delta M/M)=1.5$–$2.5$ (linear "bias"). The recognition that these cannot all be simultaneously true diffused rapidly through and beyond the astronomical community in the last year, often with a good deal of overinterpretation.

Early work on biased CDM focused on its successes in accounting for the existence and properties of galaxies and clusters, without violating observed limits on variations over the sky of the microwave background radiation (Blumenthal et al. 1984; Davis et al. 1985; Schaeffer and Silk 1985; Solovevo and Starobinskii 1985; Zabotin and Nazelsky 1985; Bardeen et al. 1986; Carlberg et al. 1986). It was, however, discovered very early (Vittorio and Silk 1985) that the largest voids, superclusters, and deviations from uniform expansion seen in the real universe are very uncommon in simulated biased CDM universes. There remained for some time, however, residual uncertainty about whether the conflict was fatal or merely serious.

It has now been accepted as fatal (Saunders et al. 1991; Hamilton et al. 1991; Kaiser 1991a; Bond 1991), in light of the combination of more and better surveys of large scale structure (Giovanelli and Haynes 1991; Rowan-Robinson et al. 1990) with more and better calculations of the products of biased CDM (Bertschinger 1991 and references therein). The simplest possible scenario just does not yield enough structure, in density or velocity, on scales much larger than 10 Mpc.

This is not quite the same as saying "the big bang is dead," or even in serious trouble, as much of the secondary scientific and popular press did in response to the paper by Saunders et al. (1991). The standard hot big bang continues to provide a good picture of all the things it can be expected to account for (Peebles et al. 1991; Schramm 1991), including nucleosynthesis, Hubble expansion, and the origins of the microwave background radiation. Similarly, the recent work has not, in any sense, disproven the existence of dark matter, or cold dark matter, or even biased cold dark matter (Frenk and Kaiser 1991). Thus, with some reluctance, I abandoned my first-choice title for this section, "lying cold and dead."

We must, however, accept some modification of the set of assumptions outlined in the first paragraph, in the direction of providing more power on large scales. As Hamilton et al. (1991) remark, almost anything you can think of to add to the scenario will do this, including baryonic material (much of which may be dark), hot dark matter, topological defects or other seeds for galaxy formation, or more complex spectra for the initial perturbations than the Harrison–Zeldovich one. Since the resulting models will have many more free parameters, they are bound to provide better fits to data on correlation functions, velocity dispersions, and so forth. We should not, therefore, lose sight of the fact that linearly biased, cold dark matter models continue to be rather successful in many contexts (Park 1991; Lilje and Lahav 1991; Park and Gott 1991; Kaiser 1991b).

10. SUPERLATIVES

It is probably a sign of intellectual immaturity that I can never resist reading a paper with a title like "First Detection of ..." or "Is NGC 9999 the largest... ." The dozen and a half items in this section are additions to (and a few subtractions from) the roster of such superlatives. They are ordered crudely from nearby to distant.

10.1 The Youngest Star?

Sandell et al. (1991) report that the luminosity of *IRAS* 4 in NGC 1333 is primarily powered by accretion and that, therefore, it may, at an age of only 10^{4-5} yr, be the youngest star yet found.

10.2 The Highest Radiative Opacities

The predicted solar neutrino flux, isochrones in HR diagrams, and whether massive stars die as red or blue supergiants all depend on the radiative opacities in stellar atmospheres and interiors. From the time of Keller and Meyerott (1955) onward, opacities found from state-of-the-art computations have been getting larger (presumably because one is more likely to discover that the previous version left out an important process than that it included a non-existent one). The trend continues for opacities cal-

culated from the OPAL code at Los Alamos National Laboratory. They are generally somewhat larger than those from the previously standard Lawrence Livermore computations. Values for the temperature and density ranges appropriate to the Sun and to Cepheids have so far been published (Iglesias and Rogers 1991a,b).

10.3 The Stars of Lowest Metallicity

The giant CS 22885-96 at [Fe/H] $= -4.2 \pm 0.2$ is the third star to turn up with less than 10^{-4} of the solar heavy element abundance (Molaro and Bonifacio 1990). It joins another giant CD $-38°245$ at -4.42 ± 0.21 and the dwarf CS 22876-32 at -4.29 ± 0.19, which, however, were published outside our official time window (Molaro and Castelli 1990).

10.4 The Longest-Period Spectroscopic Binary

70 Oph was known as a visual binary to William Herschel, and Campbell (1908) recorded radial velocity variations for it with the then-new Lick spectrograph. A combination of the Lick (1897–1932) and modern data has made it possible to derive a spectroscopic orbit independent of the visual one, confirming the 88 yr period and making 70 Oph the longest-period binary to have radial velocity data from two successive cycles (Batten and Fletcher 1991).

10.5 The Most Massive White Dwarf

White dwarfs ought to exist with masses up to the Chandrasekhar limit of 1.25–1.44 $M_\odot$ (for compositions ranging from iron to helium). The average is, however, generally believed to be only about 0.6 $M_\odot$ with quite a narrow dispersion, based on $\log g$ values from model atmosphere fits to broadband colors (Weidemann and Yuan 1989). Line profile fitting is, however, beginning to reveal stars with larger surface gravities and masses. GD 50, with $\log g$ in excess of 9.0 and corresponding mass near 1.2 $M_\odot$ (Bergeron et al. 1991) is the clearest case, G35−26, whose helium and carbon atmosphere make it more difficult to model than the hydrogen-rich GD 50, may actually be a bit more massive, with $\log g$ somewhere between 9.0 and 9.5 (Thejll et al. 1990).

10.6 The Smallest Maximum Mass for a Neutron Star

The absolute upper limit to stable neutron star masses, set by requiring that the speed of sound inside nowhere exceed the speed of light, is 3.2 $M_\odot$. Much more restrictive limits follow from using realistic equations of state for dense, degenerate neutron matter. Wu et al. (1991) suggest that the correct equation of state may be even softer than the one implied by most laboratory data, leading to a maximum stable mass of 1.56 $M_\odot$, interestingly close to the range measured in binary pulsars and X-ray sources.

10.7 The Youngest Supernova Remnant?

G25.5+0.2, initially proposed as a probable supernova remnant only about 25 yr old, is more probably outflow from a pre-main-sequence object (Zijlstra 1991). A deficit persists of very young SNRs relative to the number one might expect in a galaxy with a few supernovae per century.

10.8 The First Neutral Hydrogen in a Globular Cluster

Gas shed from the outer layers of evolving stars ought to accumulate in cluster gravitational potential wells in amounts rather larger than the limits set by early H I surveys (Knapp et al. 1973). The discrepancy has widened through the intervening years of non-detections down to levels as low as 0.1–20 $M_\odot$ for many globulars. Faulkner et al. (1991) report that they have, at long last, found about 200 $M_\odot$ of neutral hydrogen in the direction of NGC 2808. The line center velocity agrees with the velocity of the cluster, the line width matches the stellar velocity dispersion, and there is every reason to think that the gas is actually the expected cluster component.

10.9 The Most Massive Star

Stellar masses reasonably well established through binary orbits do not exceed 50–60 $M_\odot$ (Batten et al. 1989). Many of the candidates for very massive or supermassive subjects in excess of 100 $M_\odot$ have, upon closer inspection, broken up into compact clusters. Improved angular resolution from both ground and space means that this resolution into clusters is continuing, with the brightest single image, in most cases corresponding to an 80–100 $M_\odot$ star (Conti and Fitzpatrick 1991; Heydari-Malayeri and Hutsemekers 1991a,b). For the prototype of such clusters, R136 in 30 Doradus, the brightest component could be as massive as 250 $M_\odot$ (Weigelt et al. 1991) but could also itself be multiple. This leaves Melnick 42, in an uncrowded part of 30 Dor, as a likely candidate for the most massive star yet studied at about 100 $M_\odot$ (Heap et al. 1991).

10.10 The First Detection of CO in Absorption in the Milky Way

The carbon monoxide molecule, a ubiquitous tracer of molecular gas in our own and other galaxies, normally displays its ratio lines in emission. Marscher et al. (1991) have, however, reported the detection of one CO cloud in the Milky Way in absorption against the background source BL Lac.

10.11 The First Extragalactic Recurrent Nova

Recurrent novae experience nuclear detonations (not just accretion instabilities like dwarf novae, which also recur) with time intervals $\lesssim 100$ yr. Only a half dozen or so are firmly established in the Milky Way, none of them with distances well enough known to yield accurate luminosities. Nova 1990 No. 2 in the Large Magellanic Cloud turns out to have been within 2".4 of the LMC nova of 1968, and the absence of other suitable stars in the region establishes them as the same object. The 1990 outburst ejected 5×10^{-8} $M_\odot$, confirming the recurrent nova nature. The peak luminosity, at 2.9×10^{38} ergs s^{-1}, exceeded the Eddington limit, thus underlining the importance of radiation pressure in ejecting material from these systems (Shore et al. 1991).

10.12 The Lowest Metallicity Galaxy

The primordial helium abundance, an important cosmological constraint, is best established from gas abundances in galaxies with the smallest available amount of nuclear processing, as measured by their heavy element abun-

dances. The dwarf irregular (=extragalactic H II) galaxy I Zw 18 has long held the record for metal deficiency. A proposed record breaker, SBS 0335−052 (Izutov et al. 1990a, b) seems to have been a false alarm (Terlevich 1991) A couple of Byurakan galaxies (Izutov et al. 1991) and UGC 4483 in the M83 group (Skillman 1991) at any rate rival I Zw 18, whose most recent abundance determination (Campbell 1990) yielded [Fe/H]$=-1.6$. This is not quite as low as values advertised earlier, but is apparently still the record. The implied primordial helium abundance is $Y=0.23\pm0.01$ (Baldwin et al. 1991; Fuller et al. 1991).

10.13 The Biggest Black Hole?

Gas velocities can be used to trace out mass distributions in galaxies. Hα data for NGC 6240 (Bland-Hawthorn et al. 1991) suggest the presence, slightly off center, of a compact object of $10^{11}\ M_{\odot}$, a good deal larger than most of the black holes invoked to power quasars. Because the velocity on one side of the compact mass falls faster with radius than the Keplerian relation, $v\propto r^{-1/2}$, there is some possibility that nongravitational forces are dominating the gas flow, leaving the mass determination somewhat uncertain.

10.14 The Largest Quasar Redshift

Quasi-stellar objects with redshifts in excess of four demonstrate that dynamical and chemical evolution of galaxies occurred remarkably early in the history of the universe, and so press hard on many models of galaxy formation (Rees 1988). The current record belongs to Schneider et al. (1991) for PC 1247+3406 at $z=4.897$, perilously close to the value $z=5$ at which Rees says we have to start to worry.

10.15 The Largest Structures in the Universe

Both a pencil-beam redshift survey (Broadhurst et al. 1990) and counts of galaxies on plates of the Second Palomar Observatory Sky Survey (Picard 1990) reveal significant variations in the number density of galaxies on scales up to 125–140 h^{-1} Mpc. Some of the pencil-beam structure is also apparent in one survey of a larger part of the sky (Bahcall 1991). Redshifts for other comparably large samples of galaxies and clusters, on the other hand, show little or no structure at scales beyond 70–100 h^{-1} Mpc (Huchra et al. 1990; Schuecker and Ott 1991). In addition, known objects within 100–180 h^{-1} Mpc are apparently able to account for the large-scale dipole motion (deviation from uniform cosmic expansion) in which we participate (Rowan-Robinson et al. 1990; Scaramella et al. 1991; Plionis and Valdarnini 1991). The implication is that the universe is probably homogeneous beyond this point, leaving 100 h^{-1} Mpc as the characteristic scale of the largest structures. This is, of course, an enormous distance; but it is still only 3% of the Hubble radius. A comparably patchy continental United States would have about 1000 states, all smaller than Connecticut.

10.16 First Detection of the 3 K Microwave Background Radiation

I bet you thought you knew the answer to this one—Penzias and Wilson (1965)—and perhaps even the particulars of an important nondetection (Ohm 1961). I thought so too. But it seems we were wrong. The Ph.D. dissertation of LeRoux 1956 (also Denisse et al. 1957) reported an otherwise unexplained sky temperature of 3 ± 2 K, arguably the first detection, albeit one of relatively low statistical significance. Incidently, if you had ever wondered about that 1961 upper limit, a careful reading of the paper reveals that there is an extra 2 ± 1 K hiding in the estimated antenna temperature (Wilson 1991).

10.17 Most Quotable Lines

1991 yielded no acknowledgements worthy of addition to my present collection ("Words cannot express my gratitude to Prof. X."). But I spotted one fine erratum and a high-grade inoperative statement. The erratum (Shcherbakov et al. 1991) explains, "Actually, contrary to a number of previous authors, R. and R. Griffin consider that the *F* star is the primary. This has no relevance to our paper." And Gibbons (1991) presumably misspoke herself in describing an observation of "the most brilliant quasar ever observed—3C 273, in the outskirts of the Milky Way."

11. WHAT EVER HAPPENED TO...?

Newspapers and magazines occasionally devote a few columns to updates of formerly headline-grabbing, but now forgotten, news stories, thereby answering burning questions like: Can you still buy Frisbee pies?, Who really got Howard Hughes' money?, and Whatever happened to Marie McDonald? It seems only fair that we should do the same. Some of the updates resolve the original issues, some leave things rather worse off than before, and for a few one can only shake one's head and say, "very interesting." The sections are ordered so as to mix the good and bad news. The subsections are longer than in Sec. 10 because I have tried to explain what the situation was before the 1991 breakthrough(?).

11.1 FG Sagittae

FG Sagittae has been tramping around the HR diagram for at least a century, brightening fairly smoothly by four magnitudes from 1894 to 1965 (Herbig and Boyarchuk 1968) and cooling from B4 to G1$\pm$0.5 between 1955 and 1985 (Herbig and Boyarchuk 1968; Taranova 1986). In the 1970s, it started sprouting strong absorption lines of Y, Zr, Ce, La, and other *s*-process elements (Langer et al. 1974). These continued to strengthen for a decade or so and were joined by lines of Eu and Gd, normally blamed on the *r* process (Wallerstein 1990). At times the cooling went as fast as 200 K yr^{-1} (though some slowing occurred in the late 1970s, Cohen and Philips 1978), and one began to worry that the star might fall off the HR diagram completely by the end of the century. That danger has apparently been averted. From a minimum near 5650 K (Taranova 1986), FG Sge has reheated to about 6500 K and an (*IUE*) spectral type near F6-7 (Montesmos et al. 1990).

We cannot, in good conscience, say that the further behavior of the star has removed the need for making guesses about what is happening, as Herbig and Boyarchuk hoped in 1968, but at least we will be able to continue to study the star. Given the spectral types(!), the supergiant luminosity classification, and the surrounding nebulosity,

your first guess, like mine, will probably have something to do with late shell flashes in a post-asymptotic-giant-branch star.

11.2 The Solar-Neutrino Problem

No, this hasn't been solved, or you would have heard about it without reading this article, I promise. But, if the solution you prefer is oscillations among the three neutrino species catalyzed by the presence of nuclei (the MSW—for Mikhayev, Smirnov, and Wolfenstein—effect), and if, in addition, you adopt a particular mechanism (called see–saw) for calculating masses of quarks and leptons, then the masses for the electron, muon, and tau neutrino come out 10^{-8}, 10^{-3}, and 10 eV (Dar 1991). This last is just a little too small to be the dominant dark matter component in the universe, so we seem to have non-solutions for two traditional problems here.

11.3 Origin of the Anomalous Cosmic-Ray Component

First seen in the early 1970s, this excess of low-energy (3–30 MeV/nucleon), incompletely ionized helium, nitrogen, and oxygen in the cosmic rays was quickly attributed to extra-solar-system processes (reviewed, e.g., by McKibben 1987). New data, acquired from stacks of cellulose nitrate track detectors on a series of Cosmos satellite flights, reveal that the mean charge state (for instance, +0.9 for oxygen) is consistent with the most promising of these processes. The anomalous component is almost certainly interstellar matter that leaks through and is accelerated by the shock at the edge of the heliosphere (Adams et al. 1991). All is apparently well on this frontier.

11.4 The Mass of the Crab Nebula

Since late 1968, the Crab has been perceived as consisting of a 1.5 $M_\odot$ neutron star and about as much mass again in ionized gas, with an anomalously high ratio of helium to hydrogen. Because the progenitor star must have been at least 6–8 $M_\odot$, lots of people have asked "where is the rest?," without finding a definitive answer. (See Kafatos and Henry 1985 for this and much other Crab lore.)

Thus you might have thought it an improvement when MacAlpine et al. (1989) re-evaluated emission line intensities to arrive at an ionized gas mass near 6 $M_\odot$, nearly all helium. But there was a catch. To have processed that large a core into helium, the progenitor would have had to be a good deal more massive (20 $M_\odot$ or so), leaving a larger discrepancy. In addition, that big a star should have ejected new heavy elements as well as helium, and the nebula shows no evidence of such enrichment.

A sigh of relief is, therefore, the appropriate reaction to the re-re-evaluation (MacAlpine and Uomoto 1991) that returns the best estimate of the gaseous mass to 1–2 $M_\odot$, with helium abundance high but not overwhelming. Besides, I am still hoping to find some of the missing mass in the form of molecular cores of the densest filaments by means of CO observations with the Berkeley–Illinois–Maryland Array at Hat Creek this winter, or next at the latest.

11.5 Solar Oscillations

The normal modes of the Sun can be measured, at varying levels of precision, through fluctuations of luminosity, radius, and radial velocity. Many hundreds of modes, with periods from a few minutes to hours, have been classified. The most reliably identified ones are p modes, for which pressure is the restoring force. In principle, one ought to be able to invert the mode spectrum to measure solar density, composition, rotation, and convection as a function of depth. This has been done with considerable mathematical sophistication, though still with many simplifying assumptions about symmetry, unimportance of magnetic fields, and many other points (Gough and Toomre 1991).

The problem is that the solar inner workings so revealed are not quite what stellar evolution models lead us to expect for a star of 1 $M_\odot$, 1 $L_\odot$, 1 $R_\odot$ (these values are known very precisely, especially in those units), and 4.55 Gyr age (less precisely known). The mismatch (Pamyatnykh et al. 1991; Guenther 1991) is in the direction of the real solar core being less centrally condensed and the real convective envelope being more centrally condensed than the models predict. These models necessarily have even more simplifying assumptions built into them (spherical symmetry, uniform initial composition,...) than do the processed data. But both of the recent papers identify inadequate treatment of convection and mixing as the single most likely culprit.

11.6 The Decay and Death of Sciama's Particle

Sciama's (1990) dark matter candidate was a tau neutrino with a mass of 28 eV, a lifetime of 10^{23} s, a number density established by thermal equilibrium in the early universe, and a decay scheme

$$\nu_\tau \rightarrow \nu_\mu + \gamma (\approx 14 \text{ eV}).$$

It could, therefore, close the universe, ionize intra- and intergalactic gas to the observed levels when it decayed, and even tell you the value of Hubble's constant (55 ± 0.5 km s^{-1} Mpc^{-1}).

Very precisely defined hypotheses are, of course, always the easiest to rule out. The photons from the decay of the Sciamon would have yielded a fairly sharp line just blueward of Lyman alpha. The Hopkins Ultraviolet Telescope on the *ASTRO* mission looked, but the line was not there, down to a level that rules out the density-lifetime combination needed (Davidsen et al. 1991).

11.7 Progenitors of Type Ia Supernovae

For the present purpose, Type Ia supernovae are defined as the ones whose primary energy source is the explosive burning of 0.3–1.0 $M_\odot$ of carbon and oxygen (mostly) up to iron peak elements (mostly; Wheeler and Harkness 1990). One can think of several possible sites where this might happen, including the cores of single, intermediate mass stars or white dwarfs accreting from a companion (and keeping what they accrete after burning it at least to helium). But the best fit to light curves, spectral evolution, and so forth continues to come from models based on the merger of a pair of white dwarfs, with total mass exceeding the Chandrasekhar limit (Abia et al. 1991). Such a merger will inevitably occur within a Hubble time, due to loss of angular momentum in gravitational radiation, for any pair whose orbit period is less than about half a day.

One problem, however, persists. Diligent searching for radial velocity variations has failed to pick out even one pair that has both large enough mass and short enough

period to work (Bragaglia et al. 1990; Foss et al. 1991). I regard this as a serious objection to the model, though Iben (1991) disagrees.

11.8 The Gravitational Redshift of the Sun

When Einstein (1911) predicted that photons climbing out of the gravitational potential of the Sun should lose about 2×10^{-6} of their energy (equivalent to an apparent velocity of 0.6 km s^{-1}), data had already appeared (Adams 1910) showing that redshifts existed, but that the amount differed from line to line. The problem is that the solar surface has both radial and tangential gas flows, moving at about 1 km/s. These must be understood and modeled before the residual gravitational effect can be seen in photospheric lines. The task is a soberingly difficult one (Dravins 1982).

LoPresto et al. (1991) have cut the Gordian knot by looking at chromospheric emission lines—the infrared triplet of oxygen at 7772–7775 Å—in comparison with a laboratory source. Extrapolating solar disk values to the limb, they find a redshift of 0.655 km s^{-1}, equal, within the observational uncertainties, to the predicted 0.636 km s^{-1}. All is at last well here, though, as the vocabulary used by Lopresto et al. (1991) implicitly recognizes, such (first order) gravitational redshifts are a test only of the equivalence principle, not of general relativity.

11.9 Olbers' Paradox and the Holy Roman Empire

The latter, as you undoubtedly remember from high school history class, was neither Holy nor Roman nor an Empire. And Olbers' Paradox is merely a riddle, pointed out by several people before its eponymous propounder (Harrison 1987). The riddle is "why is the sky dark at night?" and, at different ages, you probably heard answers of the form "because the sun has set" and "because the universe is expanding." The first is actually more nearly to the point.

Wesson (1991) has recalculated the effects of expansion on sky brightness in a universe like the real one. The sky is darker by a factor of only 3–4 from what it would be in a static universe with the density and age of ours. To fill space with radiation at a temperature of 5000 K, the stars would have to radiate for 10^{23} yr, which their fuel supplies will not permit. Another way of looking at the numbers is that, if you stopped the expansion this afternoon and turned all the remaining hydrogen to helium, the resulting radiation energy density would correspond to a temperature of about 5.1 K. This is my favorite way of looking at the riddle, though it shows no signs of catching on.

Our rejoicing at the discovery that the expansion of the universe is not very important to the sky brightness should, perhaps, be a bit tempered by the fact that it was first made more than 25 yr ago (Harrison 1964, and remarks in Harrison 1987 and 1991). The non-recognition of this prior discovery has prompted the Editor of *Nature* to as near to a mea culpa as one can reasonably expect (Maddox 1991). My own notebook entry on the Wesson (1991) paper merely says "does not cite Harrison or total energy argument." The Holy Roman Empire was probably also not very good at record keeping.

Finally, to return to the scientific issues, it is worth remembering that the expansion effect was first invoked to account for a dark sky in a steady state universe, where the stars have been shining for 10^{23} yr. Expansion is much more important in steady state (for which the deceleration parameter $q_0=-1$) than in the Friedmann models with $q=0$–1, as is manifest in the equations provided by Harrison (1991). The mean redshift of the objects you see is $z=(1+q)^{-1}$.

11.10 At Most Four Forces

The late 1980s witnessed a flurry of claims for a fifth force, in the sense of a short-range component of gravitation that would manifest itself as an apparent violation of either the weak equivalence principle or the inverse square law. That the evidence was about to unravel was already clear at the 12th International Conference on General Relativity and Gravitation (Boulder, Colorado, July 1989; Faller 1990). The current year has seen the final laying-to-rest of evidence for deviations. Working from the top of a 300 m tower in Erie, Colorado, Speake et al. (1991) find that Newton was right, at least down to the level of accelerations of 10^{-7} m s^{-2}.

11.11 Binaries and the Initial Mass Function

The initial mass function (IMF) means the number of stars of each mass born in a unit time in a unit volume (frequently the solar neighborhood). In addition to the obvious problems of counting a complete, volume-limited sample of stars and converting observed luminosities and colors to masses and ages, unresolved binaries are a confounding factor (Scalo 1986). If the total luminosity is attributed to a single star, conversion will not yield the right mass for either the primary or the total system. In addition, if you happen to be interested in the total mass density near the Sun, you may worry that not counting the companions could leave you with a significant deficit in estimated mass compared to reality.

Both effects have been shown to be small, modulo some assumptions about the likely distributions of binary system separations and mass ratios. Binary companions can add at most 20% to the estimated local mass density (Kroupa et al. 1991), while the effect on the IMF, even for quite extreme assumptions about system properties, is small compared to the other sources of uncertainty (Piskunov and Malkov 1991).

11.12 The Spheroid of the Large Magellanic Cloud

All self-respecting spiral galaxies ought to have a spheroidal as well as a disk population of stars. And the LMC is now classified more often as Sm (Magellanic spiral) than as Magellanic Irregular. Comfortingly, therefore, investigations of both its CH stars (Cowley and Hartwick 1991) and its long-period variables (Hughes et al. 1991) reveal a population that is dynamically a spheroid, with axial ratio near 0.4 (compared to 0.6 for the Milky Way) and a mass about 2% of the total stellar mass.

12. AND ALL THE REST

The reference list that follows includes 142 items from the official year, 1991 October 1–1991 September 30. Of these, 121 are articles published in journals I normally read. During that same period, these same journals included 3070 ($\pm$50) articles that I thought should be re-

membered with at least a one-line notebook entry. The reader may deduce that I have left 96% of the important things that happened in astrophysics in 1991 out of this review. I hope this is an overestimate. But I wish there had been space to say something about triggered star formation, properties of globular cluster populations and correlations of slope of the initial mass function with metallicity, the Crab-like wisps in the Vela supernova remnant, the sizes of broad-line regions of active galaxies, magnetic fields and rotation periods of white dwarfs, the chemical composition of high-redshift galaxies and the objects that produce quasar absorption lines, and supernova rates.

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REFERENCES

Abia, C., Canal, R., and Isern, J. 1991, ApJ, 366, 199
Adams, W. S. 1910, ApJ, 31, 30
Adams, J. H., et al. 1991, ApJ, 375, L45
Alpar, M. A., et al. 1982, Nature, 300, 728
Andersen, J. 1992, A&AR, in press
Anthony-Twarog, B. J., et al. 1991, AJ, 102, 1056
Aparicio, A., et al. 1990, A&A, 240, 262.
Aparicio, A., et al. 1991, A&AS, 88, 155
Backer, D. C., et al. 1982, Nature, 300, 615
Bahcall, N. A. 1991, ApJ, 376, 43
Bailes, M., Lyne, A. G., and Shemer, S. L. 1991, Nature, 352, 311
Bailyn, C. D., and Grindlay, J. E. 1990, ApJ, 353, 159
Baldwin, J. A., et al. 1991, ApJ, 374, 580
Bardeen, J., et al. 1986, ApJ, 304, 15
Batten, A. H., and Fletcher, J. M. 1991, PASP, 103, 546
Batten, A. H., Fletcher, J. M., and MacCarthy, D. G. 1989, Publ. Dom. Astrophys. Obs. Victoria, 17, 1
Batten, A. H., Hill, G., and Lu, W. 1991, PASP, 103, 628
Beech, M. 1990, EM&P, 49, 177
Bergbusch, P. A., VandenBerg, D. A., and Infante, L. 1991, AJ, 101, 2102
Bergeron, P., et al. 1991, ApJ, 372, 267
Bertelli, G., et al. 1986, A&AS, 66, 191
Bertschinger, E. 1991, in AIP Conf. Proc. No. 222, After the First Three Minutes, ed. S. S. Holt et al. (New York, AIP), p. 297
Bland-Hawthorn, J., Wilson, A. S., and Tully, R. B. 1991, ApJ, 371, L19
Blumenthal, G., et al. 1984, Nature, 311, 405
Bond, H. E., and MacConnell, D. J. 1971, ApJ, 165, 51
Bond, H. E., and Perry, C. L. 1971, PASP, 83, 638
Bond, J. R. 1991, in AIP Conf. Proc. No. 222, After the First Three Minutes, ed. S. S. Holt et al. (New York, AIP), p. 561
Bragaglia, A., et al. 1990, ApJ, 365, L13
Broadhurst, T. J., et al. 1990, Nature, 343, 726
Brocato, E., and Castellani, V. 1991, ESO Preprint No. 774
Caloi, V., and Mazzitelli, I. 1990, A&A, 240, 262
Campbell, W. W. 1908, LOB, 5, 61
Campbell, A. 1990, ApJ, 362, 100
Campbell, D. B., et al. 1991, Science, 251, 180
Canuto, V., and Mazzitelli, I. 1991, ApJ, 370, 295
Carlberg, R., et al. 1986, ApJ, 300, L1
Castellani, V., Chieffi, A., and Straniero, O. 1990, ApJS, 74, 463
Castellani, V., Chieffi, A., and Straniero, O. 1991, ApJ, in press
Cattaneo, F., et al. 1991, ApJ, 370, 282
Chang, K., and Refsdal, S. 1979, Nature, 282, 561
Chwolson, O. 1924, Astron. Nach., 221, 329
Claret, A., and Gimeńez, A. 1991, A&AS, 87, 507
Clausen, J. V. 1991, A&A, 246, 397
Cohen, J. G., and Philips, A. C. 1980, ApJ, 237, 99
Cowley, A. P., and Hartwick, F. D. A. 1991, ApJ, 373, 80
Conti, P., and Fitzpatrick, E. L. 1991, ApJ, 373, 100
Dar, A. 1991, Science, 250, 1529
Davidsen, A. F., et al. 1991, Nature, 351, 128
Davis, M., et al. 1985, ApJ, 292, 371
Denisse, J. F., Lequeux, J., and LeRous, E. 1957, CR Acad. Sci. Paris, 224B, 3030
Dravins, D. 1982, ARAA, 20, 61
Eddington, A. 1923, Space, Time, and Gravitation (Cambridge, Cambridge University Press), p. 134
Einstein, A. 1911, Ann. Phys. Leipzig, 35, 905
Einstein, A. 1936, Science, 84, 506
Emmering, R. T., and London, R. A. 1991, ApJ, 366, 501
Falco, E. E., et al. 1991, MNRAS, 251, 698
Faller, J. E. 1990, in General Relativity and Gravitation, ed. N. Ashley et al. (Cambridge, Cambridge University Press), p. 345
Faulkner, D. J., et al. 1991, ApJ, 374, L45
Ferlet, R. 1991, Talk at STScI Workshop on Dark Matter in Galaxies, 1991 September
Foss, D., Wade, R., and Green, R. F. 1991, ApJ, 374, 281
Freeman, K. C. 1991, Talk at STScI Workshop on Dark Matter in Galaxies, 1991 September
Frenk, C. S., and Kaiser, N. 1991, Nature, 351, 22
Fruchter, A. J., et al. 1988, Nature, 333, 237
Fuller, G. M., Boyd, R. N., and Kalen, J. D. 1991, ApJ, 371, L11
Gehrels, N., et al. 1991, ApJ, 375, L13
Gibbons, A. 1991, Science, 250, 1658
Gimeńez, A. 1991, in IAU Symp., No. 151, Evolutionary Processes in Interacting Binaries, ed. Y. Kondo et al. (Dordrecht, Kluwer), in press
Giovanelli, R., and Haynes, M. P. 1991, ARAA, 29, 499
Goodman, J., and Hernquist, L. 1991, ApJ, 378, 637
Gough, D., and Toomre, J. 1991, ARAA, 29, 627
Greiner, J., Hasinger, G., and Kahabka, R. 1991, A&A, 246, L17
Griest, K. 1991, ApJ, 366, 412
Griest, K., et al. 1991, ApJ, 372, L79
Guenther, D. G. 1991, ApJ, 375, 352
Hamilton, A. J. S., et al. 1991, ApJ, 374, L1
Harrison, E. R. 1964, Nature, 204, 271
Harrison, E. R. 1987, Darkness at Night (Cambridge, MA, Harvard University Press)
Harrison, E. R. 1991, Nature, 352, 574
Heap, S. R., et al. 1991, ApJ, 377, L29
Hejlesen, P. M. 1980, A&AS, 39, 347
Herbig, G. H., and Boyarchuk, A. A. 1968, ApJ, 153, 397
Hesser, J. 1988, IAU Symp., No. 126, 66 (Dordrecht, Kluwer)
van den Heuvel, E. P. J., and Rappaport, S. A., Eds. 1991, X-Ray Binaries and the Formation of Binary and Millisecond Pulsars (Cambridge, Cambridge University Press), in press
Hewett, P. 1991, Nature, 349, 651
Heydari-Malayeri, M., and Hutsemekers, D. 1991a, A&A, 243, 401
Heydari-Malayeri, M., and Hutsemekers, D. 1991b, A&A, 244, 64
Hobbs, L. M., and Mathieu, R. D. 1991, PASP, 103, 431
Huchra, J., et al. 1990, ApJ, 365, 43
Huebner, W. F., Ed. 1990, Physics of Comets (Berlin, Springer)
Hughes, D. W. 1991, MNRAS, 251, 26p
Hughes, S. M. G., Wood, P. R., and Reid, N. 1991, AJ, 101, 1304
Hulse, R. A., and Taylor, J. H. 1975, ApJ, 195, L51
Iben, I. 1991, ApJS, 76, 55

Iglesias, C. A., and Rogers, F. J. 1991a, ApJ, 371, 408
Iglesias, C. A., and Rogers, F. J. 1991b, ApJ, 371, L73
Inoue, H. 1991, in The 28th Yamada Conference: Frontiers of X-Ray Astronomy, Nagoya, April 1991, in press
Izutov, Yu. I., et al. 1990a, AZh Lett., 16, 258
Izutov, Yu. I., et al. 1990b, AZh, 34, 343
Izutov, Yu. I., et al. 1991, A&A, 247, 303
Johnson, H. R. 1991, in IAU Symp., No. 151, Evolutionary Processes in Interacting Binary Systems, ed. Y. Kondo et al. (Dordrecht, Kluwer), in press
Johnston, H. M., and Kulkarni, S. 1991, ApJ, 366, L33
Kafatos, M. C., and Henry, R. B. C., Eds. 1985, The Crab Nebula and Related Supernova Remnants (Cambridge, Cambridge University Press)
Kaiser, N. 1991a, in AIP Conf. Proc. No. 222, After the First Three Minutes, ed. S. S. Holt et al. (New York, AIP), p. 248
Kaiser, N. 1991b, ApJ, 366, 388
Keller, G., and Meyerott, R. E. 1955, ApJ, 122, 32
King, J. R. 1991, MNRAS, 249, 658
Knapp, G. R., Rose, W. K., and Kerr, F. J. 1973, ApJ, 186, 831
Krauss, L. M., and Small, T. A. 1991, ApJ, 378, 22
Kroupa, P., Tout, C. A., and Gilmore, G. 1991, MNRAS, 251, 293
Kurfess, J. D., et al. 1991, IAUC 5323
Lang, K. R., and Whitney, D. K. 1991, Wanderers in Space (Cambridge, Cambridge University Press)
Langer, G. E., Kraft, R. P., and Anderson, K. S. 1974, ApJ, 189, 509
Leahy, D. A. 1991, MNRAS, 251, 22
Lenard, P. 1921, Ann. Phys., 65, 593
Leonard, P. J. T., and Fahlman, G. G. 1991, AJ, 102, 994
LeRoux, E. 1956, Ph.D. thesis, University of Paris
Lilje, P. B., and Lahav, O. 1991, ApJ, 374, 29
Lingenfelter, R. E., and Ramaty, R. 1989, ApJ, 343, 686
LoPresto, J. C., Schrader, C. S., and Pierce, A. K. 1991, ApJ, 376, 757
MacAlpine, G. M., and Uomoto, A. 1991, AJ, 102, 218
MacAlpine, G. M., et al. 1989, ApJ, 342, 364
Maddox, J. 1991, Nature, 352, 574
Maeder, A., and Meynet, G. 1988, A&AS, 76, 411
Maeder, A., and Meynet, G. 1991, A&AS, 89, 429
Manchester, R. M., et al. 1991, Nature, 352, 219
Mao, S., and Paczyński, B. 1991, ApJ, 374, L37
Marscher, A., et al. 1991, ApJ, 377, L77
Mateo, M., et al. 1991, AJ, 101, 892
Mathys, G. 1991, A&A, 245, 467
McKibben, R. B. 1987, Rev. Geophys. Space Phys., 25, 711
Meech, K. J., and Jewitt, D. 1987, Nature, 328, 506
Milone, E. F., Stagg, C. R., and Kallrath, J. 1991, in IAU Symp., No. 151, Evolutionary Processes in Interacting Binary Systems, ed. Y. Kondo et al. (Dordrecht, Kluwer), in press
Molaro, P., and Bonifacio, P. 1990, A&A, 236, L5
Molaro, P., and Castelli, R. 1990, A&A, 228, 426
Montesmos, B., et al. 1990, ApJ, 363, 245
Morris, M., Ed. 1989, IAU Symp., No. 136, The Center of the Galaxy (Dordrecht, Kluwer)
Motch, C., et al. 1991, A&A, 246, L24
Nadeau, D., et al. 1991, ApJ, 376, 430
Napiwotzky, N., Schönberner, D., and Weidemann, V. 1991, A&A, 243, L5
National Academy of Sciences 1991, The Decade of Discovery in Astronomy and Astrophysics ("The Bahcall Report") (Washington, DC, Natl. Acad. Sci.)
Nemec, J. M. 1989, in IAU Colloq., No. 111, The Use of Pulsating Stars in Fundamental Problems in Astronomy, edited by E. Schmidt (Cambridge, Cambridge University Press)
Nemiroff, R. J. 1991, A&A, 247, 73
Nice, D. J., et al. 1990, ApJ, 361, L61
Niel, M., et al. 1990, ApJ, 356, L21
Ohm, E. A. 1961, Bell System Tech. J., 40, 1073
Paczyński, B. 1991, ApJ, 371, L63
Pamyatnykh, A. A., Vorontsov, S. V., and Däppen, W. 1991, A&A, 248, 263
Paresce, F., et al. 1991, Nature, 352, 286
Park, C. 1991, MNRAS, 251, 167
Park, C., and Gott, J. R. 1991, MNRAS, 249, 288
Peebles, P. J. E., Schramm, D. N., Turner, E. L., and Kron, R. G. 1991, Nature, 352, 769
Penzias, A. A., and Wilson, R. W. 1965, ApJ, 142, 420
Phillips, R. J., et al. 1991, Science, 252, 651
Phinney, E. S., and Kulkarni, S. 1991, Nature, in press
Picard, A. 1991, AJ, 102, 445
Piskunov, A. E., and Malkov, D. Yu. 1991, A&A, 247, 87
Plionis, M., and Valdarnini, R. 1991, MNRAS, 249, 46
Predehl, P., Hasinger, G., and Verbunt, F. 1991, A&A, 246, L21
Pritchet, C., and Glaspey, J. W. 1991, ApJ, 373, 105
Rasio, F. A., and Shapiro, S. L. 1991, ApJ, 377, 559
Rees, M. J. 1988, in The Post Recombination Universe, NATO ASI No. 240, ed. N. Kaiser and A. N. Lasenby (Dordrecht, Kluwer), p. 101
Rowan-Robinson, M., et al. 1990, MNRAS, 247, 1
Rumor, A. 1991, in Virgil, The Aeneid, Book 4, lines 173–177
Sandell, G., et al. 1991, ApJ, 376, L17
Sarajedini, A., and Da Costa, G. S. 1991, AJ, 102, 628
Saunders, S. 1991, Eng. Sci., Spring, 15
Saunders, R. S., and Pettengill, G. H. 1991, Science, 252, 247
Saunders, W., et al. 1991, Nature, 349, 32
Scalo, J. M. 1986, Fund. Cos. Phys., 11, 1
Scaramella, R., et al. 1991, ApJ, 376, L1
Schaeffer, R., and Silk, J. 1985, ApJ, 292, 315
Schild, R. E. 1990, AJ, 100, 1771
Schneider, D. P., Schmidt, M., and Gunn, J. E. 1991, AJ, 102, 837
Schramm, D. N. 1991, in AIP Conf. Proc. No. 222, After the First Three Minutes, ed. S. S. Holt et al. (New York, AIP), p. 12
Schuecker, P., and Ott, H. A. 1991, ApJ, 378, L1
Sciama, D. W. 1991, Comm. Astrophys., 15, 71
Shcherbakov, A. G., et al. 1991, A&A, 247, 590
Shore, S., et al. 1991, ApJ, 370, 193
Skaley, D., and Stix, M. 1991, A&A, 241, 227
Skillman, E. D. 1991, PASP, 103, 919
Solovevo, L. V., and Starobinskii, A. A. 1985, AZh, 29, 367
Speake, C. C., et al. 1991, Phys. Rev. Lett., 65, 1957
Stetson, P. B. 1991, AJ 102, 589
Stothers, R. B. 1991, ApJ, in press
Strobel, A. 1991, Astron. Nach., 312, 177
Sullivan, W. 1991, Continents in Motion, 2nd ed. (New York, AIP)
Sunyaev, R. A. 1991, Talk at 12th Texas Symposium on Relativistic Astrophysics (Brighton, UK, December 1990), quoted in S&T, 91, 576
Sunyaev, R. A., et al. 1991a, AZh Lett., 17, 42, 50, and 54
Sunyaev, R. A., et al. 1991b, IAU Circ., Nos. 5204 and 5245
Tanaka, Y. 1991, in IAU Symp., No. 151, Evolutionary Processes in Interacting Binary Systems, ed. Y. Kondo et al. (Dordrecht, Kluwer), in press
Taranova, O. G. 1986, Astrofizica, 24–25, 616
Terlevich, E. 1991, Talk at 21st General Assembly of the International Astronomical Union (Buenos Aries, July 1991)
Thejll, P., et al. 1990, ApJ, 361, 197
Thorstensen, J. R., et al. 1991, AJ, 102, 688
Trimble, V. 1987, ARAA, 25, 425
Trimble, V. 1991, in IAU Symp., No. 151, Evolutionary Processes in Interacting Binary Systems, ed. Y. Kondo et al. (Dordrecht, Kluwer), in press
VandenBerg, D. A. 1985, ApJS, 58, 711
Vittorio, N., and Silk, J. 1985, ApJ, 293, L1
Wallerstein, G. 1990, ApJS, 74, 755
Walsh, D., Carswell, R. F., and Weymann, R. J. 1979, Nature, 279, 381
Wambsganss, J., and Paczyński, B. 1991, AJ, 102, 864

Weidemann, V., and Yuan, J. W. 1989, in IAU Colloq., No. 114, White Dwarfs, Lecture Notes in Phys. No. 328, ed. G. Wegner (Berlin, Springer), p. 1
Weigelt, G., et al. 1991, ApJ, 378, L21
Wesson, P. S. 1991, ApJ, 367, 399
West, R. M., Hainaut, O., and Smette, A. 1991, A&A, 246, L77
Wheeler, J. C., and Harkness, R. A. 1990, Rep. Prog. Phys., 53, 1467
Wilson, R. W. 1991, in Modern Cosmology in Retrospect, ed. B. Bertotti et al. (Cambridge, Cambridge University Press), p. 291
Wu, X., et al. 1991, A&A, 246, 411
Yamauchi, S., and Koyama, K. 1990, PASJ, 42, L83
Zabotin, N. A., and Nazelsky, P. D. 1985, AZh, 29, 239
Zijlstra, A. A. 1991, MNRAS, 248, 11p
Zwicky, F. 1937, Phys. Rev., 51, 290 and 679